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Effects of Non-traditional Additives on the Early Strength of a Lean Clay Soil Stabilized by Compound Calcium-based Stabilizer

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Abstract

Soil stabilization is a widely used technique in civil engineering to enhance the engineering properties of fine-grained soils. Traditional calcium-based stabilizers, such as cement, lime (L), and fly ash (FA), are most commonly used due to their availability and proven effectiveness. However, these stabilizers often exhibit slow early strength development. To address this challenge, the present study explores the potential of non-traditional additives to improve early strength in stabilized soils. A range of additives, including two nano-materials, six soluble sodium and calcium salts, five soluble iron and aluminum salts, and cationic polyacrylamide (CPAM), were incorporated into a lean clay soil stabilized with a compound calcium-based stabilizer composed of cement, L, and FA. The 7-day unconfined compressive strength (UCS) was used as the primary performance indicator. The results indicated that within the tested dosage ranges, the two nano-materials, most soluble iron and aluminum salts, and CPAM had minimal or even adverse effects on early strength development. In contrast, specific combinations of soluble sodium salts significantly enhanced early strength. For example, a combination of 0.05% sodium carbonate with 0.05% sodium silicate, and 0.05% sodium sulfate with 0.05% sodium silicate, resulted in strength increases of 34.5% and 33.6%, respectively. Additionally, the standalone addition of 0.5% water glass led to a 32.2% improvement in strength.

Keywords

soil stabilization, additives, early strength, calcium-based stabilizer, clayey soil

1 Introduction

Clayey soil is a natural, multi-scale, and multi-phase mixture formed through the combined effects of geological and biological cycles. The predominant inorganic particles in clayey soils are clay minerals, which originate from the weathering of rocks in the geological cycle and typically exist in the form of fine, plate-like sheets [1, 2]. These minerals have a strong affinity for water, leading to varying degrees of volume expansion when exposed to moisture. Upon water absorption, a diffused double-layer (DDL) structure forms at the surface of the soil particles. When the DDL is thin, inter-particle forces remain strong, endowing the soil with desirable engineering properties. However, as the DDL thickens and transitions into a free-water-containing membrane, the distance between particles increases beyond the effective range of these forces, causing the soil to become plastic, or even turn to slurry [1–4]. This sensitivity of clayey soils to moisture changes results in fluctuations in volume and strength, which restricts their suitability for engineering applications. The inherent instability of clayey soils poses significant risks to buildings and structures constructed on them, threatening safety and incurring substantial annual costs [4–6].

Soil stabilization is a cost-effective technique for enhancing the engineering properties of fine-grained soils, especially clayey soils [3–5]. Traditionally, this process involves uniformly mixing various inorganic, organic, or biological materials into the soil, with or without added water. The mixture is then compacted at its optimum moisture content, followed by a curing period. Through chemical and/or physico-chemical reactions within the mixture, soil properties such as strength, stiffness, compressibility are improved, while volumetric changes due to moisture fluctuations are minimized [5, 6]. This conventional approach is particularly effective for clayey soils with a moisture

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content near their optimum water content and is widely applied in compacted soil filling applications, including pavement bases, subbases, embankments, canal and reservoir linings, shallow foundations, stabilized rammed earth structures, and more, especially beneficial in areas where coarse aggregates are scarce or where transportation costs are prohibitively high [4, 7, 8]. In recent years, however, the scope of soil stabilization has expanded to include methods like deep mixing and in-situ solidification. These techniques are specifically designed for treating clayey soils with higher moisture content, including soils with water content several times their liquid limit, and generally do not require compaction process. In this article, soil stabilization refers to the first technique.

Among the many materials used in soil stabilization, lime (L) and Portland cement (PC), commonly known as calcium-based stabilizers, are predominantly favored for their widespread availability and proven effectiveness. Although, in recent years, greater emphasis has been placed on utilizing various industrial wastes or by-products, such as fly ash (FA), ground granulated blast-furnace slag (GGBS), cement kiln dust (CKD), rice husk ash (RHA), red mud, polyacrylamide copolymers, bioenergy coproduct and geopolymer materials, to replace cement and L for soil stabilization in the pursuit of carbon reduction [3–6], the wide availability and mature production processes of cement and L are unmatched by these industrial wastes or by-products. Moreover, numerous studies and engineering applications have demonstrated the effectiveness of cement and L in the field of soil stabilization. Therefore, research on calcium-based stabilizers remains of significant importance.

Although the stabilization mechanism of calcium-based stabilizers involves a range of complex chemical and physico-chemical processes, including cation exchange, flocculation and agglomeration (particle restructuring), cementitious hydration, carbonation, and pozzolanic reaction [3, 6], the primary reaction in the stabilizer-soil-water system can be described as the dissolution of reactive constituents of both the stabilizer and the soil, followed by the precipitation of calcium gels such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), along with other calcium-based binding materials [9–11]. Water plays a crucial role in the dissolution-precipitation process. However, during the compaction of stabilizer-soil-water mixture, it is typically necessary to maintain the water content close to the optimal moisture content to achieve the maximum dry density [12–15]. Therefore, after compaction, the stabilizer-soil-water system is unsaturated with limited water content, which impedes the dissolution-precipitation processes in the mixture. Furthermore, reactions in the stabilizer-soil-water mixture such as pozzolanic reactions between calcium hydroxide and active silica and aluminum oxides usually proceed at slower rates [16, 17]. Consequently, many unreacted stabilizer particles remain in the compacted soil at the early age. Therefore, low early strength becomes one of the major challenges for the calcium-based stabilized soils.

In order to overcome the delayed early strength development, efforts have been made to introduce novel constituents into the calcium-based stabilizer-soil mixture, aiming to accelerate the reaction processes. For instance, Handy [18] conducted a study on the effects of alkalis on the strength of cement-soil, and found that adding a certain amount of sodium hydroxide to the mixing water can significantly enhance the early strength of soil-cement. Davidson et al. [19] investigated the effects of three chemical additives on the strength of L-treated soils, revealing that a 1–3% concentration of sodium hydroxide can double the strength of clay soils, whereas sodium phosphate decreases the strength and sodium carbonate yields inconsistent results. Mateos and Davidson [20] observed that a 1% dosage of sodium hydroxide, sodium carbonate, sodium metasilicate, and sodium chloride reduced the strength of clayey soil. Zhang et al. [21] systematically examined the influence of L and FA-based stabilizers, with sodium chloride, calcium chloride, sodium sulfate, calcium sulfate, potassium hydroxide, sodium carbonate, potassium carbonate, potassium permanganate, and sodium silicate as additives, on the early strength of the stabilizer-soil mixture. The results indicated that sodium carbonate, sodium hydroxide, sodium sulfate, sodium silicate, and sodium phosphate can promote the early strength of L-FA soil. Modmoltin and Voottipruex [22] found that the addition of $CaCl_2$ to cement-treated clay can increase the strength of clay-cement mixture. In summary, different type of salts have different or even controversial effects on the strength development of calcium-based stabilized soils. Apart from salts, other materials have also been included to promote the early strength of the stabilized soils, such as nano-materials, RHA, silica fume, industrial by-products and others. The effects of these materials still need a further verification.

This study explores the effects of non-traditional additives on the early strength development of a locally sourced lean clay soil stabilized with a compound calcium-based stabilizer. The stabilizer, comprising PC, L, and FA, was initially blended with the dried soil at a mass ratio of 4:2:1:100 (PC:L:FA:dry soil) to form a base mixture. Subsequently, various dosages of non-traditional additives, including two nano-materials, six soluble sodium and calcium salts, five soluble iron and aluminum salts, and cationic polyacrylamide (CPAM), were then incorporated into the base mixture. The prepared mixtures were then statically compacted into cylindrical specimens (50 mm in height and 50mm in diameter) at the optimum moisture content. After a 7-day curing period, unconfined compression tests were conducted to evaluate the efficiency and cost-effectiveness of the chosen additives in improving early strength. Furthermore, this study examined the impact of different methods of additive incorporation and the synergistic effects of certain additive combinations on the early strength development. The findings aim to provide valuable insights for selecting appropriate additives to optimize soil stabilization using calcium-based stabilizers.

2 Materials and methods

2.1 Materials

2.1.1 Soil

The soil used in the tests is a natural yellowish-brown muddy soft soil taken from the bottom of a 1.5 m deep borrow pit near Hangzhou, China, which does not contain large particles of sand or gravel. According to the Unified Soil Classification System (ASTM D2487-17 [23]), the soil used is classified as lean clay (CL) type. After drying at the temperature of 105 °C for 3 days, the soil is pulverized to pass No. 4 (4.75 mm) sieve [24]. The particle size distribution of the dried soil is shown in Fig. 1. Table 1 shows the physical and chemical properties of the soil. The XRD pattern shown in Fig. 2 indicates that the soil mainly contains clay minerals of clinochlore, montmorillonite, and illite; and other minerals such as quartz and muscovite. The results of semi-quantitative analysis of chemical elements by EDAX spectrometer indicate that the soil contains little organic matter or sulfate. An inductively coupled plasma emission spectrometer (ICP-OES) was adopted to analyze the heavy metal pollutants in the nitric acid extract of soil samples and the results show that the soil is "clean" type and permitted to be used in engineering projects.

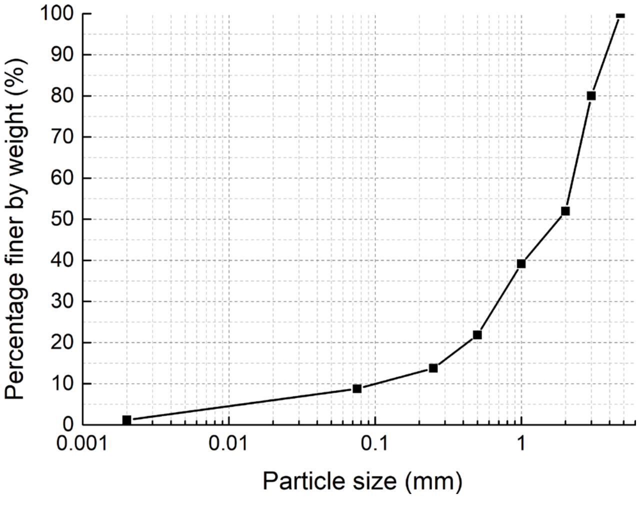

Fig. 1 Soil particle size distribution

2.1.2 Compound calcium-based stabilizer

The calcium-based stabilizer (named as B2) used in the study is composed of cement, L and FA with a ratio of 4:2:1. The raito of the compound calcium-based stabilizer is verified to be the optimal for the chosen soil by our former study [15]. The cement is Type 325 Ordinary Portland cement, which is produced by local Qianchao Portland Cement Company (Hangzhou, China). The L used in the research is provided by Hangzhou Tuohai Corporation (Hangzhou, China), which is a finely grounded L powder with 85% total content of CaO and MgO. The FA is high calcium Class C FA obtained from Shaoxing Shangyu Hangzhou-union cogeneration Co., Ltd. (Shaoxing, China). Table 2 presents the chemical composition of the three materials.

2.1.3 Additives

The additives tested in this study were selected based on their efficiency and the underlying reaction mechanisms. Nano-materials were chosen for their large specific surface area and high chemical reactivity, which can significantly accelerate the pozzolanic reaction. Inorganic salts were included due to their ability to react with calcium-based stabilizers and their ease of incorporation into the mixtures. CPAM was selected for its long molecular chains, which effectively attract soil particles and enhance agglomeration:

1. Nano-materials
   Nano-SiO_2 and nano-Al_2O_3 used in the tests are produced by Nanjing Haitai Nanomaterial Co., Ltd. (Nanjing, China). The nano-SiO_2 type is HT-Si-01 and the nano-Al2O3 type is HTAl-01-A.
2. Inorganic salts
   Ferric sulfate ($Fe_2(SO_4)_3 \cdot nH_2O$), aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$), ferric chloride ($FeCl_3 \cdot 6H_2O$), aluminum chloride ($AlCl_3 \cdot 6H_2O$), calcium chloride ($CaCl_2$), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), sodium silicate ($Na_2SiO_3 \cdot H_2O$),

Table 1 Physical and chemical properties of soil sample

Natural dry density (g/cm^3)	Dried moisture content (%)	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index	Activity of clay	Distilled water (pH)	1 M KCl solution (pH)	Carbon content (wt.%)	Sulphur content (wt.%)
1.64	2.94	2.69	37.8	19.3	18.5	2.02	6.55	5.86	1.59 ~ 4.25	0 ~ 0.77

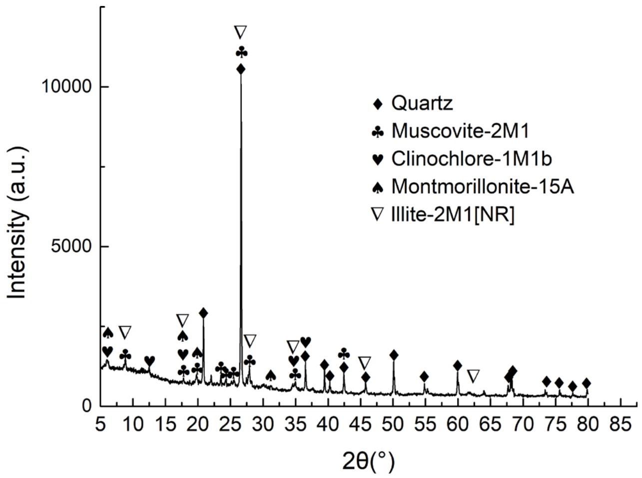

Fig. 2 Mineral composition of the soil

Table 2 Chemical composition of the calcium-based stabilizers

Materials	Chemical compositions (mass fraction (%))								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2	SO_3
PC	18.04	8.79	4.96	54.14	0.12	0.32	3.56	–	1.77
L	–	–	–	86.26	–	–	0.68	–	–
FA	11.61	21.73	1.75	40.28	0.95	1.36	0.49	1.66	0.61

sodium sulfate (Na_2SO_4), potassium aluminum sulfate dodecahydrate ($KAl(SO_4)_2 \cdot 12H_2O$) are all analytical pure chemical reagents produced by Shanghai Hushi Laboratory Equipment Co., Ltd. (Shanghai, China). Water glass ($Na_2O \cdot 3.3SiO_2$) is produced by Jiaxing Tongxiang Hengli Chemical Co., Ltd. (Jiaxing, China), with a modulus of 3.3.

3. Cationic polyacrylamide
   CPAM is produced by Henan Tengfei Environmental Protection Technology Co., Ltd. (Zhengzhou, China), with a molecular weight of 12 million.

2.2 Experimental program

2.2.1 Additives test scheme

Nano-materials

Nano-SiO_2 and nano-Al_2O_3 at dosages of 1.5%, 2.5%, and 3.5% by weight of the calcium-based stabilizer was separately introduced into the B2 stabilizer by dry mixing. During specimen preparation, the compaction degree was set at 96%, and six parallel specimens were made for each mixture combination. A set of B2 specimens were also made for control.

Soluble sodium and calcium salts

The test plan of soluble sodium and calcium salts is shown in Table 3. All soluble salts were added to the stabilizer-soil mixture in an aqueous solution manner rather than dry mixing. For specimen molding, two specimens were made for each combination at compaction degrees of 94%, 96%, and 98%, respectively.

Soluble iron and aluminum salts

The test plan was set to add the five soluble iron and aluminum salts at dosages of 0.1%, 0.3%, and 0.5% by dry soil weight, separately, into the mixture of B2 stabilizer and soil. The five salts were introduced in the form of aqueous solution. During specimen preparation, the compaction degree was set at 96%, and three parallel specimens were made for each mixture combination.

Cationic polyacrylamide

The CPAM was tested on three different addition manners: dry mixing, emulsion, and surface brushing after specimen moulding. The dosage for dry mixing was 0.2%, while for the emulsion (and surface brushing) the dosage

Table 3 Soluble sodium and calcium salt addition scheme

Combinations	Sodium salt					Calcium salt
	Sodium carbonate (%)	Sodium silicate (%)	Sodium sulfate (%)	Sodium hydroxide (%)	Water glass (%)	Calcium chloride (%)
a1	0.1	–	–	–	–	–
a2	–	0.1	–	–	–	–
a3	–	–	0.1	–	–	–
a4	–	–	–	0.1	–	–
a5	–	–	–	–	–	0.1
a6	0.05	0.05	–	–	–	–
a7	–	0.05	0.05	–	–	–
a8	0.05	–	0.05	–	–	–
a9	0.033	0.033	0.033	–	–	–
b1	0.3	–	–	–	–	–
b2	–	0.3	–	–	–	–
b3	–	–	0.3	–	–	–
b4	–	–	–	0.3	–	–
b5	–	–	–	–	–	0.3
b6	0.15	0.15	–	–	–	–
b7	–	0.15	0.15	–	–	–
b8	0.15	–	0.15	–	–	–
b9	0.1	0.1	0.1	–	–	–
c1	0.5	–	–	–	–	–
c2	–	0.5	–	–	–	–
c3	–	–	0.5	–	–	–
c4	–	–	–	0.5	–	–
c5	0.25	0.25	–	–	–	–
c6	–	0.25	0.25	–	–	–
c7	0.25	–	0.25	–	–	–
c8	0.167	0.167	0.167	–	–	–
d1	–	–	–	0	0.5	–
d2	–	–	–	0.1	0.5	–
d3	–	–	–	0.3	0.5	–
d4	–	–	–	0.5	0.5	–

was 0.1%. During moulding, the compaction degree was set at 94% and 96%, and six parallel specimens were made for each mixture combination.

2.2.2 Test procedures

As shown in Fig. 3, the experimental procedures primarily consisted of compaction testing, specimen preparation and curing, and unconfined compression testing, conducted in accordance with the Chinese Standard JTG E51-2009 [24]. Firstly, the B2 stabilizer was evenly blended with the dried soil at a mass ratio of 4:2:1:100 (PC:L:FA:dry soil) to form a base mixture. The maximum dry density and optimum moisture content of the mixture were then determined to be 1.79 g/cm^3 and 15%, respectively, using the modified Proctor compaction test. Subsequently, various dosages of non-traditional additives were added to the base mixture. The resulting mixtures were then statically compacted into cylindrical specimens, each measuring 50 mm in height and 50 mm in diameter, at their optimum moisture content using a 30 kN hydraulic pressing machine. Then, the compacted specimens were transferred to a curing room maintained at a temperature of 20 ± 1 °C and a relative humidity of 95 ± 5%. After a 7-day curing period, unconfined compression tests were conducted on all specimens using a 30 kN hydraulic pressing machine at a displacement rate of 1 mm/min. More detailed experimental procedures can be found in our previous study [15].

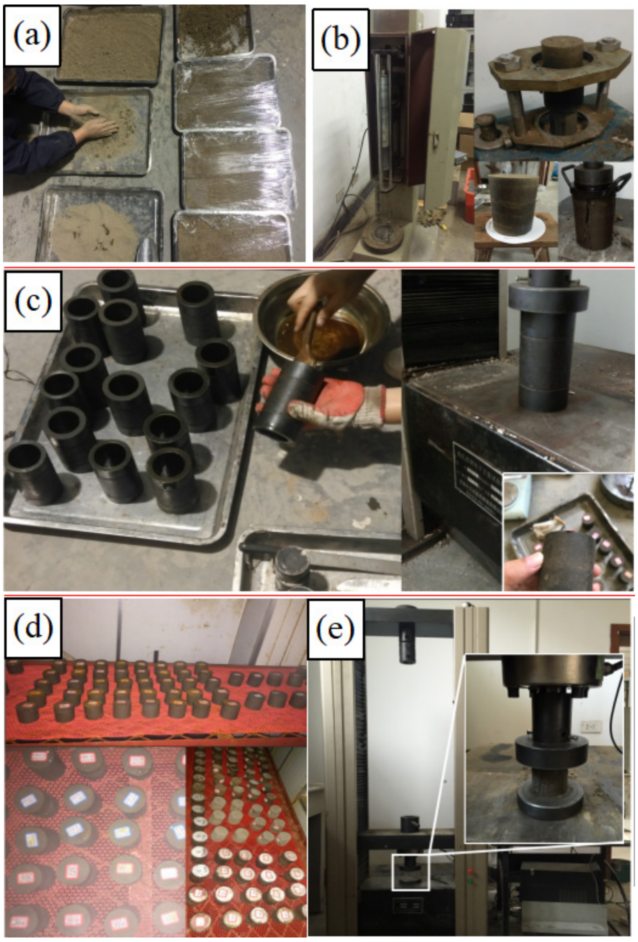

Fig. 3 The main experimental procedures: (a) base mixture preparation and mixing; (b) compaction test; (c) specimens molding; (d) specimens curing; (e) unconfined compression test

3 Results and discussion

3.1 Nano-SiO_2 and nano-Al_2O_3

Fig. 4 presents the 7-day unconfined compressive strength (UCS) values of specimens incorporating various dosages of nano silica and nano alumina into the base mixture. The results indicate that within the investigated dosage range (1.5%–3.5%), the 7-day UCS of specimens with added nano silica or nano alumina shows minimal variation (−1.04% to +4.31%) compared to specimens prepared solely with the base mixture. The highest strength improvement, an increase of 4.31%, was observed with the combination of B2 and 1.5% nano-Al_2O_3, while the largest reduction, −1.04%, occurred with B2 and 3.5% nano-Al_2O_3. These findings suggest that the addition of nano silica or nano alumina does not significantly influence the early strength of the base mixture.

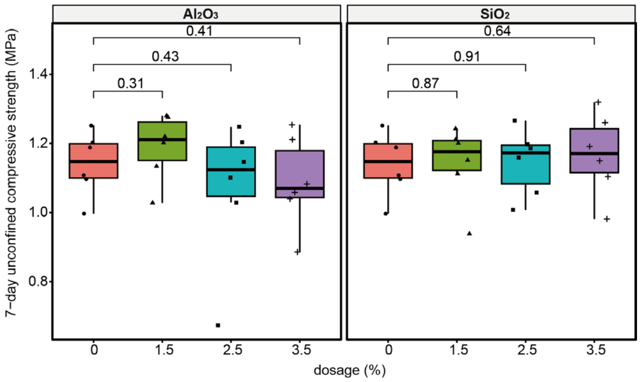

Fig. 4 The 7-day UCS with different dosages of nano materials

Previous studies [25, 26] have shown that nano silica and nano alumina enhance strength primarily by promoting the formation of additional CSH and CAH through pozzolanic reactions. However, both materials are inherently non-reactive and require sufficient activators and a conducive environment to realize their full potential. In this study, the limited content of the calcium-based stabilizer and the lack of an interconnected free water film [1] likely restricted the activation and reactivity of the nano materials. Consequently, their ability to improve the bonding between soil particles was diminished. Moreover, the ultra-fine particle size of the nano materials may have further impeded their uniform dispersion within the stabilizer-soil mixture during the dry mixing process, resulting in uneven distribution and reduced efficacy. These factors may collectively account for the negligible variations in UCS observed across specimens with different dosages of nano silica and nano alumina.

3.2 Soluble sodium and calcium salts

Figs. 5 to 7 present the 7-day UCS of specimens incorporating different types of sodium and calcium salts. A consistent trend is observed across all specimens, where the UCS increases with higher compaction degrees, typically by 2% to 15% per increment. This observation aligns with findings from previous studies, which attribute the strength enhancement to a reduction in porosity and an increase in contact points between soil particles [13, 27]. These structural changes enhance inter-particle molecular forces, thereby improving the overall strength of the specimens [2, 28].

At a dosage of 0.1% by dry soil weight (Fig. 5), specific combinations of sodium salts – namely a2, a6, a7, a8, and a9 – significantly enhance the early strength of the base mixture. Combination a6 (0.05% sodium carbonate + 0.05% sodium silicate) achieves the highest UCS improvement, with a 34.5% increase, followed closely by combination a7 (0.05% sodium sulfate + 0.05% sodium silicate), which shows a 33.6% increase. In contrast, the combination of equal amounts of sodium sulfate, sodium silicate,

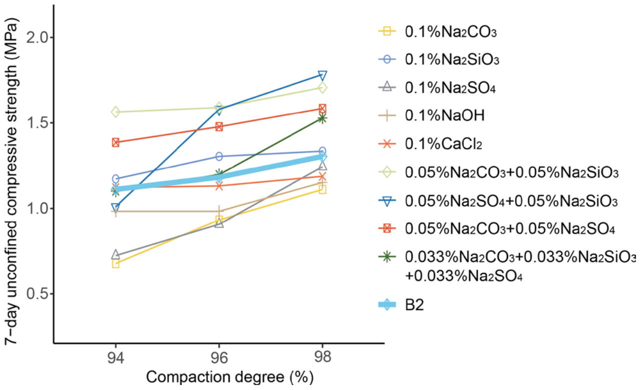

Fig. 5 The 7-day UCS of specimens with a dosage of 0.1% salts

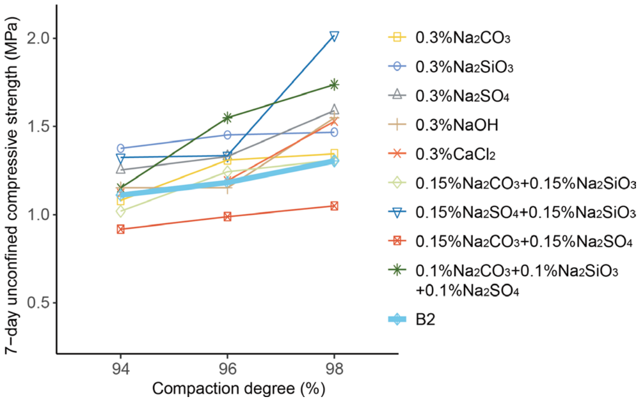

Fig. 6 The 7-day UCS of specimens with a dosage of 0.3% salts

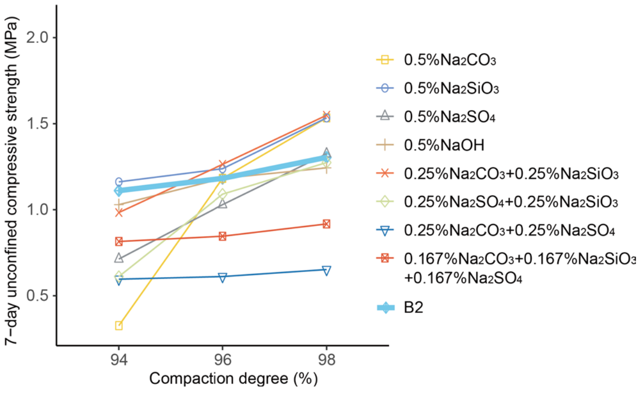

Fig. 7 The 7-day UCS of specimens with a dosage of 0.5% salts

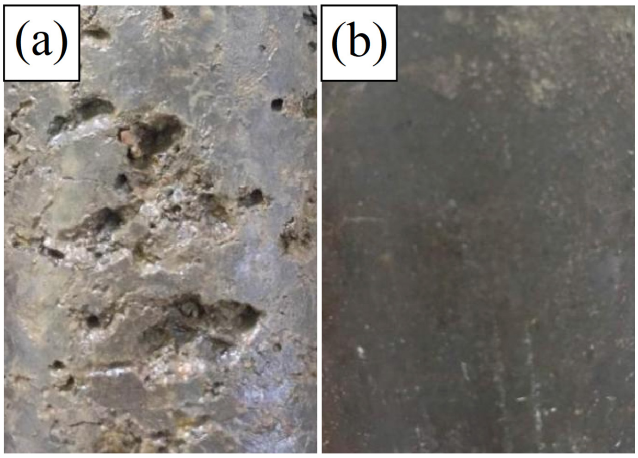

Fig. 8 Surface comparison: (a) Etching pits on the surface of specimens added with 0.3% soluble sodium salts; (b) the surface of B2 specimens and specimens added with B2 and 0.3% $CaCl_2$

and sodium carbonate yields the lowest improvement, with a strength increase of just 1%.

At a dosage of 0.3% dry soil weight (Fig. 6), combinations b1, b2, b3, b7, and b9 exhibit a strength increase compared to the base B2 stabilizer-soil mixture. However, the magnitude of their strength enhancement is lower than that achieved by the combination of 0.05% sodium carbonate and 0.05% sodium silicate. Notably, after 24 h of water immersion curing on the seventh day, varying degrees of surface etching pits were observed on specimens incorporating 0.3% soluble sodium salts (Fig. 8(a)). The most severe etching was found on the surfaces of specimens containing sodium carbonate or sodium sulfate individually. In contrast, the surfaces of specimens stabilized with B2 alone or with calcium chloride appeared relatively smooth, with no visible etching pits (Fig. 8(b)).

At a dosage of 0.5% dry soil weight (Fig. 7), all sodium salt combinations yielded strength increments of less than 15%. Additionally, specimens containing higher dosages of sodium salts exhibited increased surface erosion, with the combination of sodium carbonate and sodium sulfate showing the most significant surface deterioration. Among the sodium salts tested, sodium silicate caused the least erosion, followed by a combination of sodium sulfate and sodium silicate.

The results indicate that appropriate combinations of soluble sodium and calcium salts significantly enhance the early strength of the calcium-based stabilized soils, consistent with previous studies [21]. Sodium silicate, sodium carbonate, and sodium sulfate readily dissolve into the soil solution, releasing CO_3^{2-}, SiO_3^{2-} and SO_4^{2-} ions. These ions react with calcium ions (Ca^{2+}) released from L and cement in the B2 stabilizer, forming cementitious compounds such as calcium carbonate ($CaCO_3$), calcium silicate ($CaSiO_3$), and calcium sulfate ($CaSO_4$). These reactions not only contribute directly to strength development but also increase the concentration of hydroxyl ions (OH^-) in the soil solution. The elevated OH^- concentration facilitates the dissolution of soil minerals and FA, promoting the formation of geopolymeric cementitious materials and further enhancing early strength.

However, the study also reveals that excessive sodium salt content (above 0.3% by dry soil weight) can result in surface erosion, which is likely due to the formation of soluble sodium compounds. This hypothesis is supported by the observation that etching pits appeared only after the water immersion curing process, suggesting that prolonged exposure to water may have facilitated the dissolution or migration of these soluble compounds, leading to localized degradation of the specimen surfaces.

Fig. 9 presents the strength characteristics of specimens incorporating a 0.5% dosage of water glass combined with varying amounts of sodium hydroxide. The results reveal a progressive decline in strength as the dosage of sodium hydroxide increases. Specimens without sodium hydroxide exhibited higher strength than those with it. Notably, 0.5% water glass alone resulted in a 32.2% strength increase compared to the base mixture. This suggests that the molar ratio of SiO_2 to Na_2O in water glass plays a critical role in influencing the strength of calcium-based stabilized soils. Increasing the sodium hydroxide dosage decreases the SiO_2/Na_2O molar ratio in water glass, resulting in decreased early strength. These findings are consistent with previous research [29, 30] and highlight the importance of optimizing the composition of water glass to achieve the desired stabilization performance.

3.3 Soluble iron and aluminum salts

Fig. 10 illustrates the UCS values of specimens cured for 7 days with varying dosages of iron and aluminum salts. The results show that, with the exception of potassium alum, specimens containing other soluble iron or aluminum salts exhibit lower strength compared to those stabilized with the B2 stabilizer, with reductions ranging from 3.0% to 26.8%. The addition of potassium alum at varying dosages (0.1%, 0.3%, and 0.5% by dry soil weight) resulted in strength increases of 4.4% to 22.7%, with the highest improvement observed at the 0.5% dosage. In contrast, specimens incorporating aluminum sulfate, iron sulfate, or iron chloride showed a decreasing strength trend as the salt dosage increased. This reduction in strength can be attributed to the hydration of these salts in water, which generates significant amounts of H^+ ions. The presence of H+ ions consumes the OH^- released by the calcium-based stabilizer, thereby hindering the formation of key cementitious compounds such as CSH and CAH gels [31, 32].

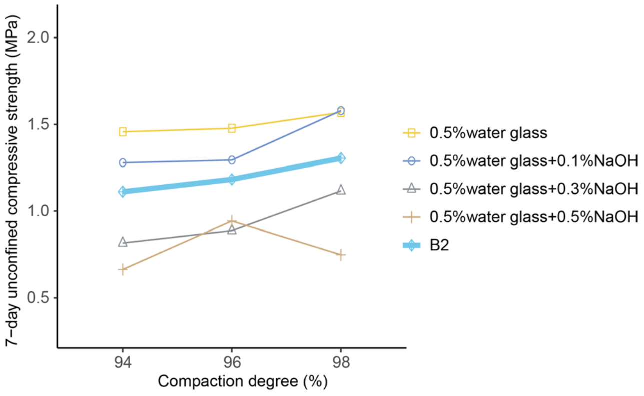

Fig. 9 The 7-day UCS of specimens with 0.5% water glass and 0.1% ~ 0.5% sodium hydrate

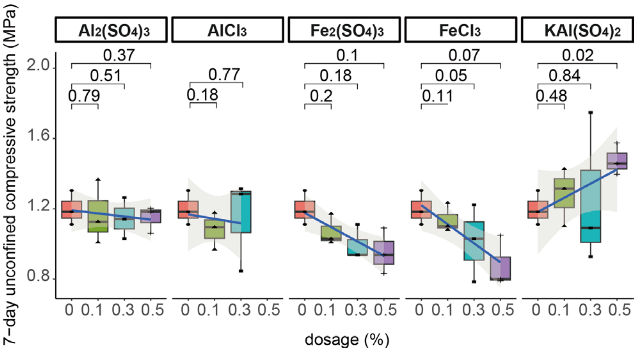

Fig. 10 The 7-day UCS of specimens with different dosages of iron and aluminum salts

3.4 Cationic polyacrylamide

When 0.2% CPAM was incorporated into the B2 stabilizer-soil mixture through dry mixing, the specimens exhibited severe cracking after a 7-day curing period, as illustrated in Fig. 11. The load capacity of the specimens was significantly lower than that of the base mixture, indicating a detrimental effect of CPAM on the structural integrity. This behavior can be attributed to the volumetric expansion of CPAM upon water absorption [33]. The CPAM used in this study has a high molecular weight of 12 million, and its dosage is considerably higher than typical applications as a flocculating agent. During the curing process, CPAM absorbs water, resulting in significant swelling, stretching of molecular chains, and eventually causing cracking in the specimens.

The strength of specimens incorporating 0.1% CPAM through emulsion and surface brushing techniques at

Fig. 11 Specimens cracking with a dosage of 0.2% CPAM by dry mixing

compaction degrees of 94% and 96% is presented in Fig. 12. The data indicate a decrease in strength (ranging from 10.7% to 49.1%) for both types of specimens when CPAM is included. The mechanism underlying this strength reduction remains unclear. One possible explanation is that CPAM's strong water affinity competes with the stabilizer-soil mixture for moisture, potentially impeding the hydration and pozzolanic reactions between the calcium-based stabilizer and soil. This interference could reduce the formation of cementitious compounds, thereby weakening the overall structure.

4 Conclusions

To identify efficient and cost-effective additives for enhancing the early strength of calcium-based stabilized soils, this study investigated the effects of various non-traditional additives on the 7-day UCS of a lean clay soil stabilized with a compound calcium-based stabilizer (B2). The additives included two nano-materials, six soluble sodium and calcium salts, five soluble iron and aluminum salts, and CPAM, which were introduced either through dry mixing or in solution form. Based on the experimental results, the following conclusions can be drawn:

1. Effect of nano-materials

   Within the dosage range of 1.5% to 3.5% by dry soil weight, the addition of nano silica or nano alumina had a negligible impact on the 7-day UCS of the specimens, with variations ranging from −1.04% to +4.31% compared to the B2 stabilizer alone. These results suggest that nano-materials in the tested dosages are not effective in significantly enhancing the early strength.
2. Effect of soluble sodium and calcium salts

   Among the tested combinations, adding 0.05% sodium carbonate and 0.05% sodium silicate by dry soil weight in solution form yielded the highest UCS improvement, with a strength increase of 34.5%. This was followed by a combination of 0.05% sodium sulfate and 0.05% sodium silicate, which achieved a 33.6% strength increase. However, when the dosage of soluble sodium salts exceeded 0.3% by dry soil weight, soluble compounds formed within the stabilized soil, resulting in surface etching pits after water immersion and a decline in strength. Additionally, the strength of specimens increased with compaction degree, typically by 2% to 15% for each degree of increase.

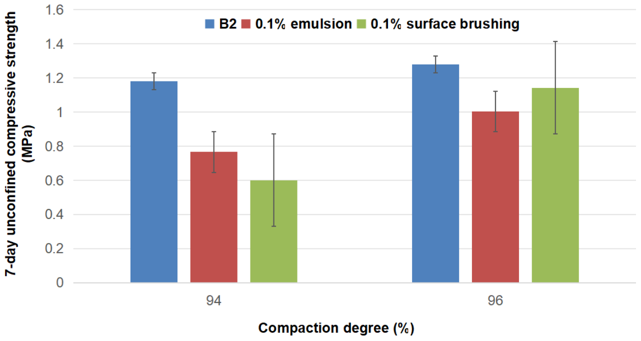

Fig. 12 The 7-day UCS of specimens with a dosage of 0.1% CPAM added by emulsion and surface brushing

3. Effect of water glass and sodium hydroxide

   Among combinations of water glass and sodium hydroxide, the addition of 0.5% water glass alone to the B2 stabilizer-soil mixture resulted in the highest UCS improvement of 32.2%. For combinations including sodium hydroxide, the UCS of specimens decreased progressively as the sodium hydroxide dosage increased from 0.1% to 0.5%, which is likely due to decreased SiO_2/Na_2O molar ratio in the water glass.
4. Effect of soluble iron and aluminum salts

   Among the investigated iron and aluminum salts (dosage range: 0.1% to 0.5% of dry soil weight), only potassium aluminum sulfate dodecahydrate (potassium alum) had a positive impact, increasing the UCS by 4.4% to 22.7%. In contrast, aluminum sulfate, iron sulfate, and iron chloride caused strength reductions of 3.0% to 26.8%, with a linear decrease in strength as their dosages increased. These reductions are attributed to the H^+ ions released from the hydration of these salts, which consume hydroxide ions and hinder the formation of key cementitious compounds.
5. Effect of cationic polyacrylamide (CPAM)

   The addition of CPAM, at dosages of 0.1% to 0.2% by dry soil weight, led to a reduction in the 7-day UCS of the B2 stabilizer-soil mixture regardless of the addition method (dry mixing, emulsion, or surface brushing). The strength reductions are likely due to the strong water affinity of CPAM, which may interfere with the hydration and pozzolanic reactions of the calcium-based stabilizer.

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